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AUTHOR <i>EW</i> EJ Mets NW Roberts <i>NR</i>	SUBJECT CLASSIFICATION Fatigue of Metals	NO. 57TP469 DATE 7-10-57
TITLE Fatigue Characteristics of Aluminized and Galvanized Plain Forged Steel		
ABSTRACT		

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Title Page

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ABSTRACT A preliminary fatigue study has been made - to evaluate the effect of hot dip aluminizing and galvanizing of plain forged steel (1040 carbon).				
G.E. CLASS 3		REPRODUCIBLE COPY FILED TECHNICAL DOCUMENTS		NO. PAGES 15
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CONCLUSION The test results show a 45% decrease in fatigue strength due to aluminizing and a 27.8% decrease in fatigue strength due to galvanizing. These results indicated that both galvanizing and aluminizing can have deleterious effects on the fatigue properties of ball bolts. Further evaluation should be made on the following variables: 1. Specimen surface finish and size effect. 2. The effect of bath temperatures, immersion time and the metallurgical structures of the coating and base material. 3. Reduction in fatigue life due to preloads. (Project 23-2-2)				

By cutting out this rectangle and folding on the center line, the above information can be fitted into a standard card file.

For list of contents-drawings, photos, etc. and for distribution see reverse side.

INFORMATION PREPARED FOR Insulator Department

TESTS MADE BY E. J. Mets - N. W. Roberts

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BUILDING and ROOM No. 7-223 LOCATION Transformer Division, Pittsfield

CONTENTS OF REPORT

NO PAGES TEXT

NO CHARTS

DRAWING NOS.

57TP469

8

178H412, 178H413, 178H414

Sketch No. 3

PHOTO NOS. Fig. 1 and 2

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Hickory
7-305
7-223
Schen.
43-554
7-315
8B-22
Rome
Holyoke
Oakland
7-223
7-223
7-217
7-323
7-213
Insulator Dept.
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WH Airgood
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TITLE SHEETS

Hickory
Insulator Dep
42-506
43-568
Rome
27-388
16-210
8B-39
42-506
43-550
8B-22
Hudson F.
7-213
Schen.
43-322
43-382

Report No. 57TP469

-1-

INTRODUCTION

The ball bolts used by the Insulator Department are a forged AISI 1040 carbon steel. The recommended design strength is taken as 50%, 24,500 psi, of the minimum ultimate tensile strength for the material. The actual minimum strength is 48,800 psi, and the maximum strength is 71,500 psi.

In actual use, the insulator strings experience appreciable vibration and reversal of load which becomes the critical design feature rather than pure tensile loading. It is because of this phenomena that the Process Development Section of the Pittsfield Transformer Laboratories Department was requested to evaluate the fatigue characteristics of the ball bolt vs. a galvanized or aluminumized ball bolt of the same material. This report is a joint evaluation by the Metallurgical and Process Development Sections of the Transformer Laboratories Department.

OBJECT OF INVESTIGATION

The purpose of this investigation was to evaluate the fatigue characteristics of insulator ball bolt material; and further, to determine the effect of hot dip aluminizing and galvanizing on the fatigue strength of the as-received plain forged steel bolts.

MATERIAL TESTED

The ball bolt material is a plain forged steel, AISI 1040. The material has a maximum ultimate tensile strength of 71,500 psi and a minimum ultimate tensile strength of 48,800 psi. The ball bolts were procured from the Insulator Department.

SAMPLE PREPARATION

Samples were machined and hand polished to the dimensions shown in Figure 3. After machining, one third of these samples were aluminized and a second third galvanized.

Aluminizing Procedure

Preparation of the samples, prior to hot dipping, consisted of the following:

1. Vapor degreasing
2. HCl pickle for 4 min. at 80°C
3. Cold water rinse
4. Air drying

When completely dried, the samples were immersed into a commercially pure Al bath (99.0% Al) for 2 min. at 720°C. Upon removal from the bath, and as soon as the coating had solidified, they were water quenched to room temperature.

Galvanizing Procedure

Preparation prior to galvanizing was the same as described above for aluminizing. After cleaning, the samples were immersed into the galvanizing kettle for 1 min. at a temperature of 465°C. Salammonic flux covered the Zn bath. Upon solidification of the coating, these samples were also water quenched.

METHOD OF TEST

The fatigue test was a tension compression cyclic test with zero mean stress, no preload.

The fatigue test was conducted in a Baldwin-Lima-Hamilton Universal Fatigue Machine, Model No. SF-1-U, 1000 pound capacity, inertia type fatigue machine.

To expedite these tests, a theoretical fatigue curve, $C = N \cdot (S-Se)^2$, was established for each test condition. Se is the endurance limit stress, S the fatigue or cyclic stress, N the number of cycles to failure related to the cyclic stress and C a constant related to the elastic constants for the material.

Basing the S-N diagrams or fatigue curves on ten million cycles as infinite life expectancy, the graphs 178H412 through 178H414 were determined as follows:

For each curve, two specimens were run in the fatigue machine at different stress levels and then cycles to failure determined. Using these results, the fatigue curves were determined theoretically and plotted, along with their normal distribution curves.* The theoretical fatigue curve was then checked by running more specimens at different stress levels and have been plotted on the theoretical curve. See Appendix A and B in TIS Report 54TP431 which discusses the theoretical fatigue curve and normal distribution curves in detail.

RESULTS

Also see attached sheets for test data.

<u>Test Specimen</u>	<u>Endurance Limit</u>	<u>Fatigue Limit (psi)</u>
Plain forged steel		34,600
Galvanized		25,000
Aluminized		21,000

Coating Thickness and Structure

After fatigue testing, one aluminized and galvanized sample was cross sectioned and examined microscopically for structure and coating thickness. These structures are shown in photomicrographs of Figure 1 and 2. In both cases there is a marked similarity in their structure and thickness. The coatings are composed of two distinct layers, the interfacial layer, and the outer metal layer. The average coating thickness values of the samples examined are as follows:

	<u>Total thickness,</u> <u>mils</u>	<u>Interfacial layer,</u> <u>mils</u>	<u>Outer layer,</u> <u>mils</u>
Aluminized	4	1.5	2.5
Galvanized	4	1.0	3.0

* See page 7 for sample calculation.

Although there is a similarity between these structures, there is a significant difference in the formation of the alloy interfacial layer. The diffusion of Al into the base steel is along a very irregular front, while the galvanized alloy layer forms along a relatively smooth front.

It is interesting to note the differences in the cracking patterns formed in these two coatings after fatigue tests. In the galvanized coating, the cracks appear to originate at the surface and propagate laterally for some distance through the outer coating layer. The cracks then proceed downward and appear to be arrested at the interfacial layer. In contrast, the Al coating shows fracture only in the brittle interfacial layer.

DISCUSSION

1. Fatigue Aspect

The theoretical fatigue curves as presented are based on the premises of: the material absorbs a certain amount of energy at stress levels above the endurance limit, but less than the proportional limit and is cumulative, the energy absorbed per cycle is some portion of the available energy being supplied above the endurance limit, and after N cycles, the limiting amount of energy that can be absorbed by the material is reached and fracture occurs.

As in all fatigue tests, the data is influenced by an inherent statistical scatter. The scatter bands presented were based on the assumption that the number of cycles to fracture was a normal distribution and that the coefficient of variation is constant. Assuming a coefficient of variation of 33%, the standard deviation would be $0.33 \bar{N}$. The scatter bands drawn, therefore, become $0.33 \bar{N}$ for the poorest samples and $1.66 \bar{N}$ for the best samples. These envelopes will include 95% of all test points, if the statistical distribution is actually a normal one. The two envelopes will converge to the same endurance limit which is a hypothetical graph constructed on the basis of the assumed distribution.

With these assumptions in mind, the three S-N diagrams were plotted and the test results show more scatter than the normal distribution predicts; this being true for all cases investigated. However, in fatigue work the most important part of an S-N curve is the endurance limit value, where the curve becomes asymptotic to the time axis. In all cases, the specimens were tested at stress levels close to the theoretical endurance limit stress and found to survive the 10,000,000 cycle life cycle, or fracture well beyond this acceptable life cycle.

It is on this basis that the S-N diagrams, theoretical endurance limits, have been accepted as relative indication of the effect of aluminizing and galvanizing the plain forged steel insulator ball bolts.

2. Metallurgical Aspect

The phenomena of cracking as shown by the aluminized coating after fatigue test may be expected because of the brittle nature of the interfacial layer. The lack of such cracking in the brittle alloy layer of the Zn coating is difficult to explain. Earlier investigators¹, who have noted the serious effects of galvanizing on the fatigue properties of steel, all agree that the endurance limit is reduced by the brittle Fe-Zn alloy layer in which cracks form that propagate through the steel. The higher loss in strength as shown by the aluminized steels in this test may well be due to the notch effects and higher stress concentrations set up by the irregular front of the interfacial layer. In addition, the effect of bath temperature alone may have some effect on this loss in strength.

The presence of a hot dip metallic coating on steel complicates the fatigue evaluation considerably. This is due to a number of variables present in coating preparation and their subsequent effects on the coating and base steel structures. It should not be assumed that a part will develop the average fatigue strength indicated by laboratory tests unless it is certain that the test specimens represent the metallurgical structures and stresses present in the actual part.

The data obtained from this test presents true values for the samples tested and do indicate that hot dip coatings can affect the fatigue properties of steel to a large and possibly serious proportion. However, further work is necessary to determine whether these results represent the low, high or average values for actual coated steel ball bolts.

¹ W. E. Harvey, "Zinc as a Protective Coating Against Corrosion - Fatigue of Steel", Metals & Alloys, 1 458 (April, 1930).

CONCLUSIONS

The test results show a 45% decrease in fatigue strength due to aluminizing and a 27.8% decrease in fatigue strength due to galvanizing. These results indicated that both galvanizing and aluminizing can have deleterious effects on the fatigue properties of ball bolts.

The results of this test bear out the same order of decreasing strength tension-wise on recent tests conducted on carriage bolts from Mr. B. R. Hermann. See Test Report PDM-57-131.

SUGGESTIONS FOR FURTHER TEST

This test did not attempt to evaluate the numerous variables that were present. A more elaborate program should be conducted to determine the significant difference caused by such variables as:

1. Specimen surface finish, and size effect.
2. The effect of bath temperatures, immersion time on the metallurgical structures of the coating and base material.
3. Reduction in fatigue life due to preloads.

Sample Calculation of Theoretical Fatigue Curves

Table 3 - Plain forged steel aluminized

Specimens 2 and 3 results were used in this calculation.

Nomenclature - S_e = Endurance limit stress
 S_1 = Cyclic stress of larger stressed sample
 S_2 = " " " smaller " "
 N_1 = Cycles to failure of S_1
 N_2 = " " " " S_2
 C = A constant related to the elastic constants for the material.
 $\bar{N}$ = Mean numbers of cycles at a stress level.

Sample No. 2

S_1 = 27,100 psi
 N_1 = 274,000 cycles

Sample No. 3

S_2 = 25,000 psi
 N_2 = 669,000 cycles

$$S_e = \frac{\sqrt{\frac{N_2}{N_1}} S_2 - S_1}{\sqrt{\frac{N_2}{N_1}} - 1}$$

$$S_e = \frac{\sqrt{\frac{669}{274}} (25,000) - 27,100}{\sqrt{\frac{669}{274}} - 1} = \frac{38,900 - 27,100}{0.56}$$

S_e = 21,000 psi Theoretical Fatigue Limit

Calculation of Constant "C"

$$C = N_2 (S_2 - S_e)^2 = 66.9 \times 10^4 (25,000 - 21,000)^2$$

$$C = 1070 \times 10^{10}$$

Therefore, the equation for the Theoretical Fatigue Curve becomes

$$\bar{N} = \frac{1070 \times 10^{10}}{(S - S_e)^2}$$

And by using S_e = 21,000 psi and assuming a range of cyclic stresses S the corresponding mean number of cycles to failure can be computed and a graph plotted as shown, see graph 178H414. Also included on each curve is a statistical band based on a normal statistical distribution about the mean and a constant coefficient of variance equal to 33%.

TABLE 1
Plain Forged Steel

Specimen No.	Cyclic Stress (psi)	Cycles to Failure	Remarks
1*	43,100	5,000	Fracture fillet
2	34,500	12,123,000	No fracture
3	38,800	194,000	Fracture fillet
4	36,600	305,500	" "
5*	35,300	783,000	" "

TABLE 2
Plain Forged Steel Galvanized

Specimen No.	Cyclic Stress (psi)	Cycles to Failure	Remarks
1	32,500	229,000	Fracture fillet
2*	28,000	408,000	" "
3	25,200	17,282,000	No fracture
4*	27,000	876,000	Fracture fillet
5	26,000	15,096,000	No fracture
6	26,500	225,000	Fracture fillet

TABLE 3
Plain Forged Steel Aluminized

Specimen No.	Cyclic Stress (psi)	Cycles to Failure	Remarks
1	26,000	419,000	Fracture fillet
2*	27,100	274,000	" "
3*	25,000	669,000	" "
4	23,100	930,000	" "
5	21,500	18,665,000	" "
6	22,000	455,000	" "

*Specimen results used for calculating theoretical fatigue curve.

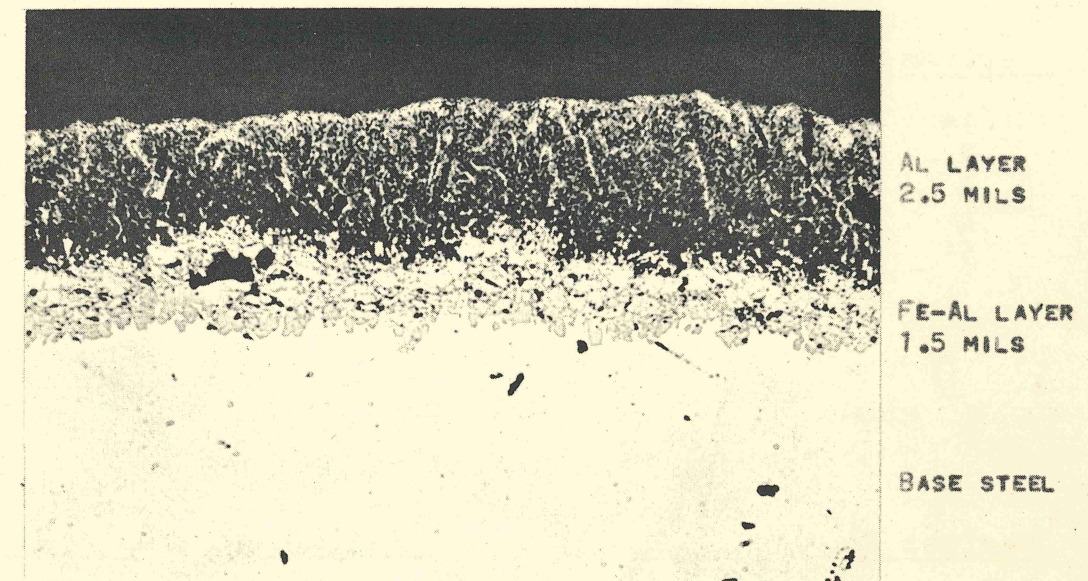


FIGURE 1 - MICROSTRUCTURE OF HOT DIP ALUMINUM COATING SHOWING FRACTURING OF FE-AL LAYER AFTER FATIGUE TEST. X250

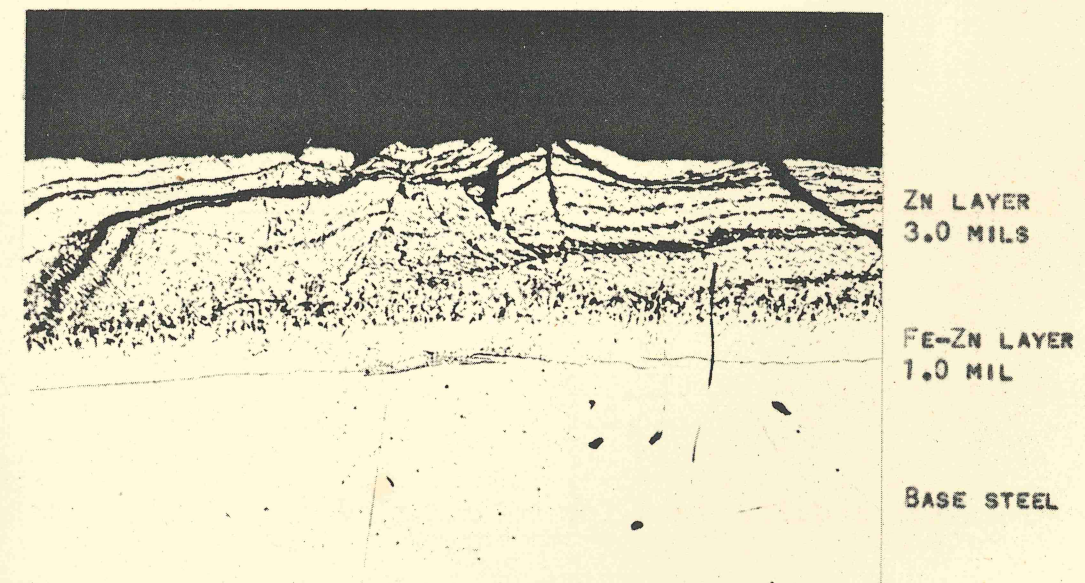
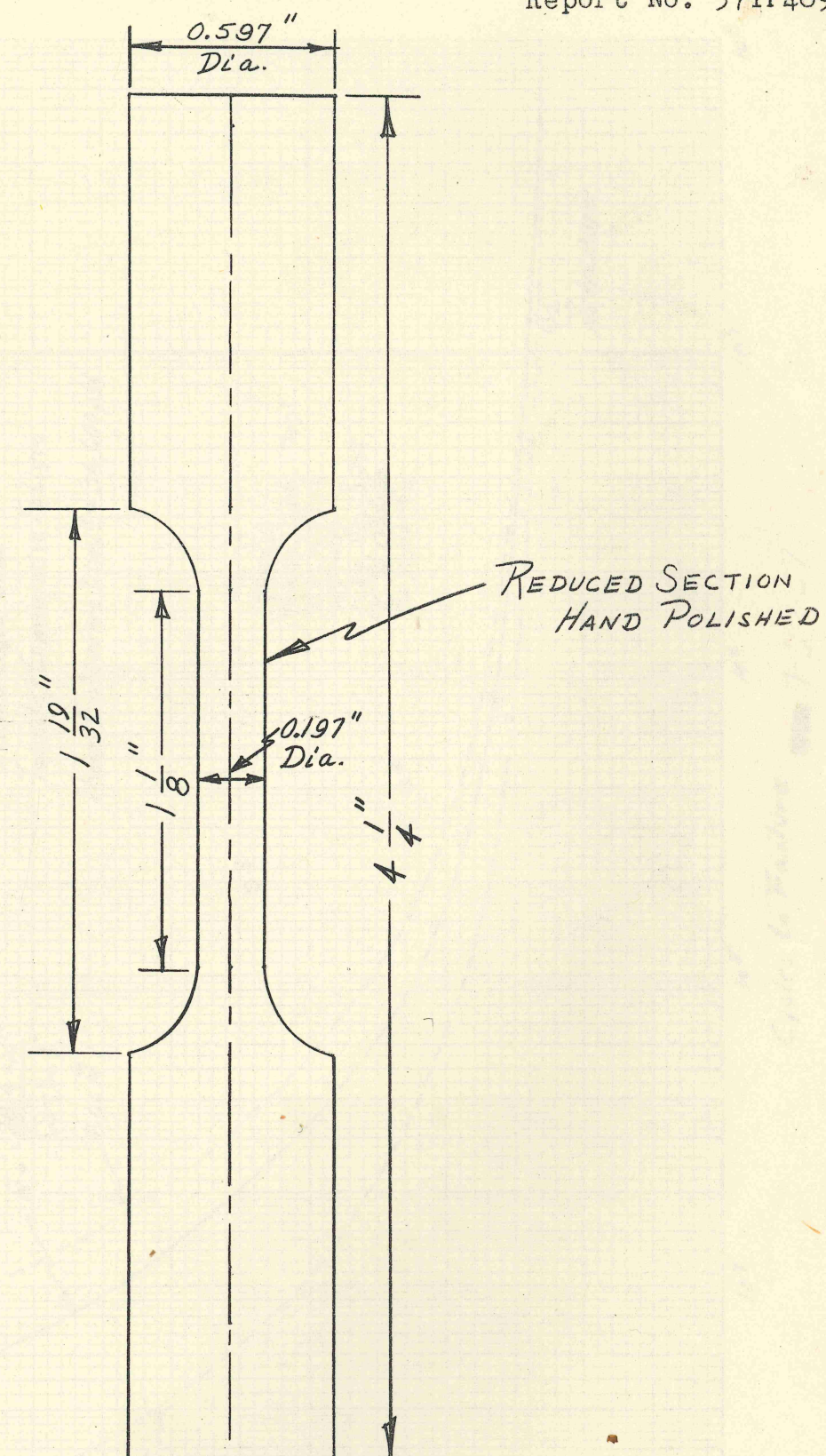


FIGURE 2 - MICROSTRUCTURE OF GALVANIZED COATING. NOTE CRACKING OF THE ZN LAYER AFTER FATIGUE TEST. X250

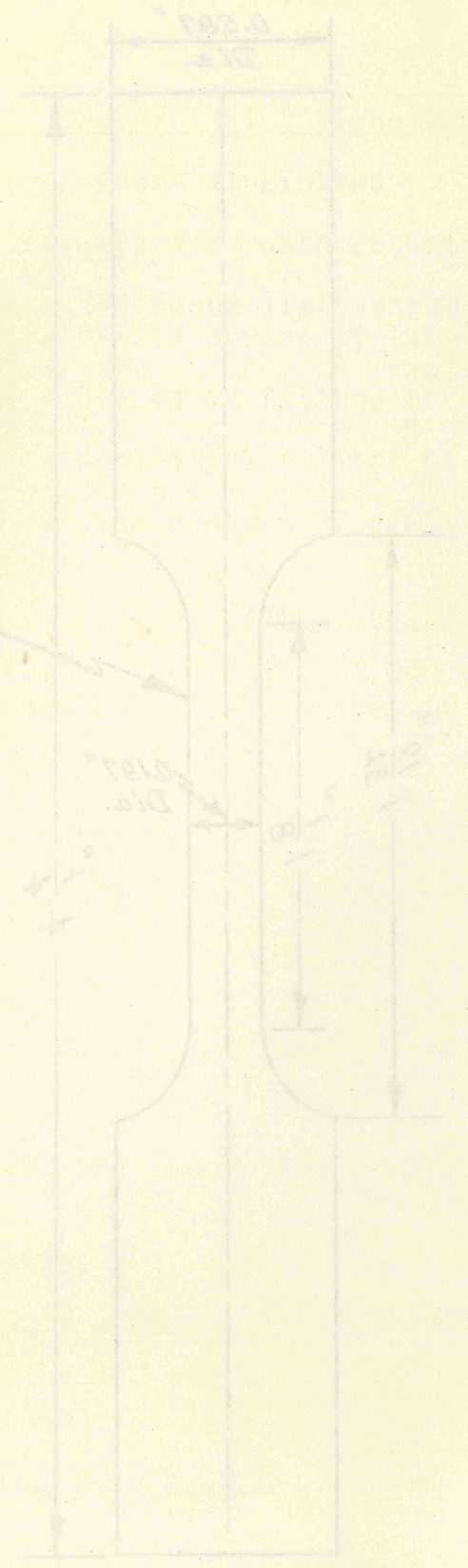


Fatigue Specimen

Sketch No. 3

Report No. 5775-69

Reduced Section
Hand Forged



Fatigue Specimen
Sketch No. 3

FN-522-A (8-50)

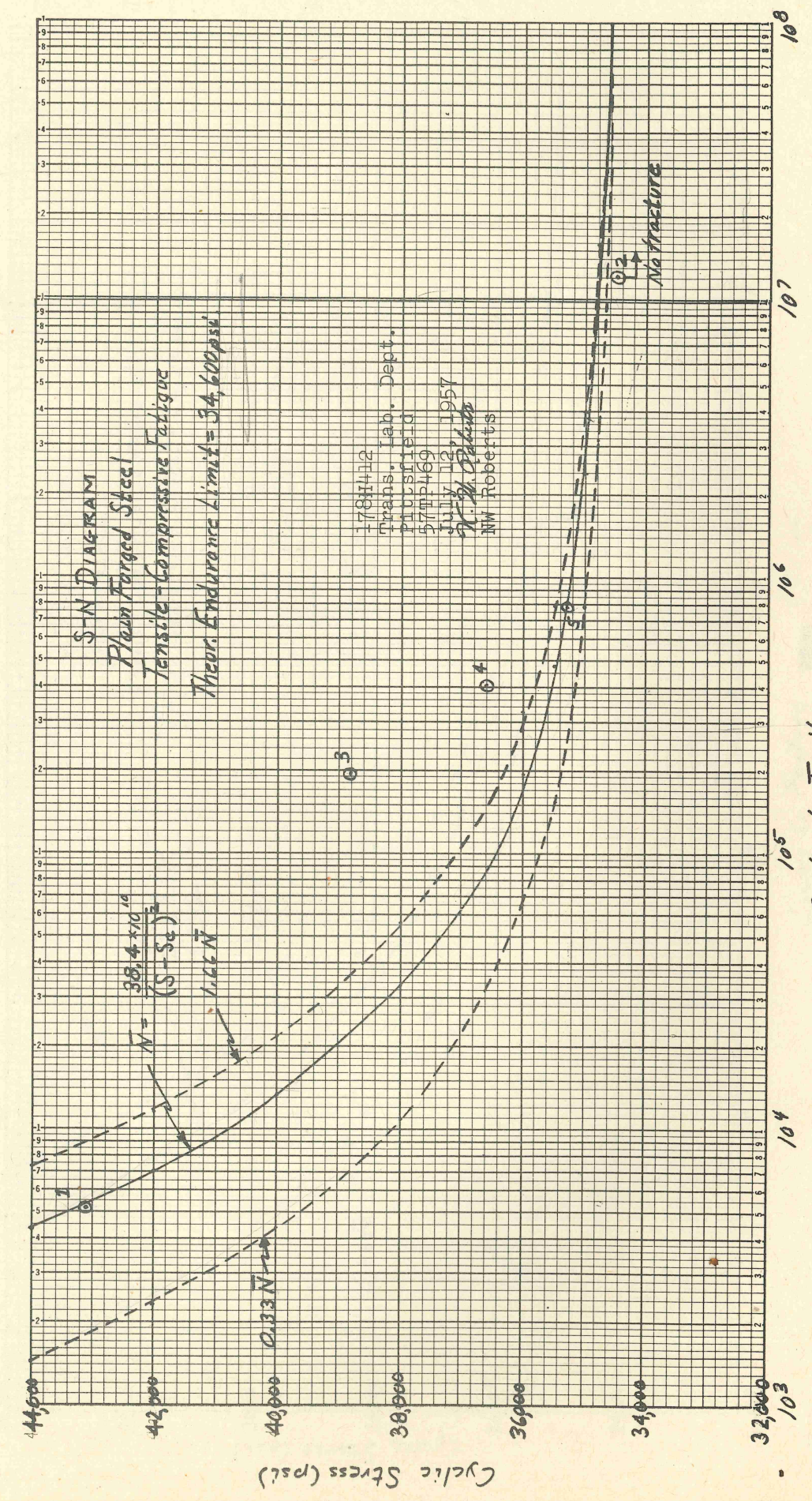
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4 Log Cycles X 60 Divisions

4 Log Cycles X 60 Divisions

178H412

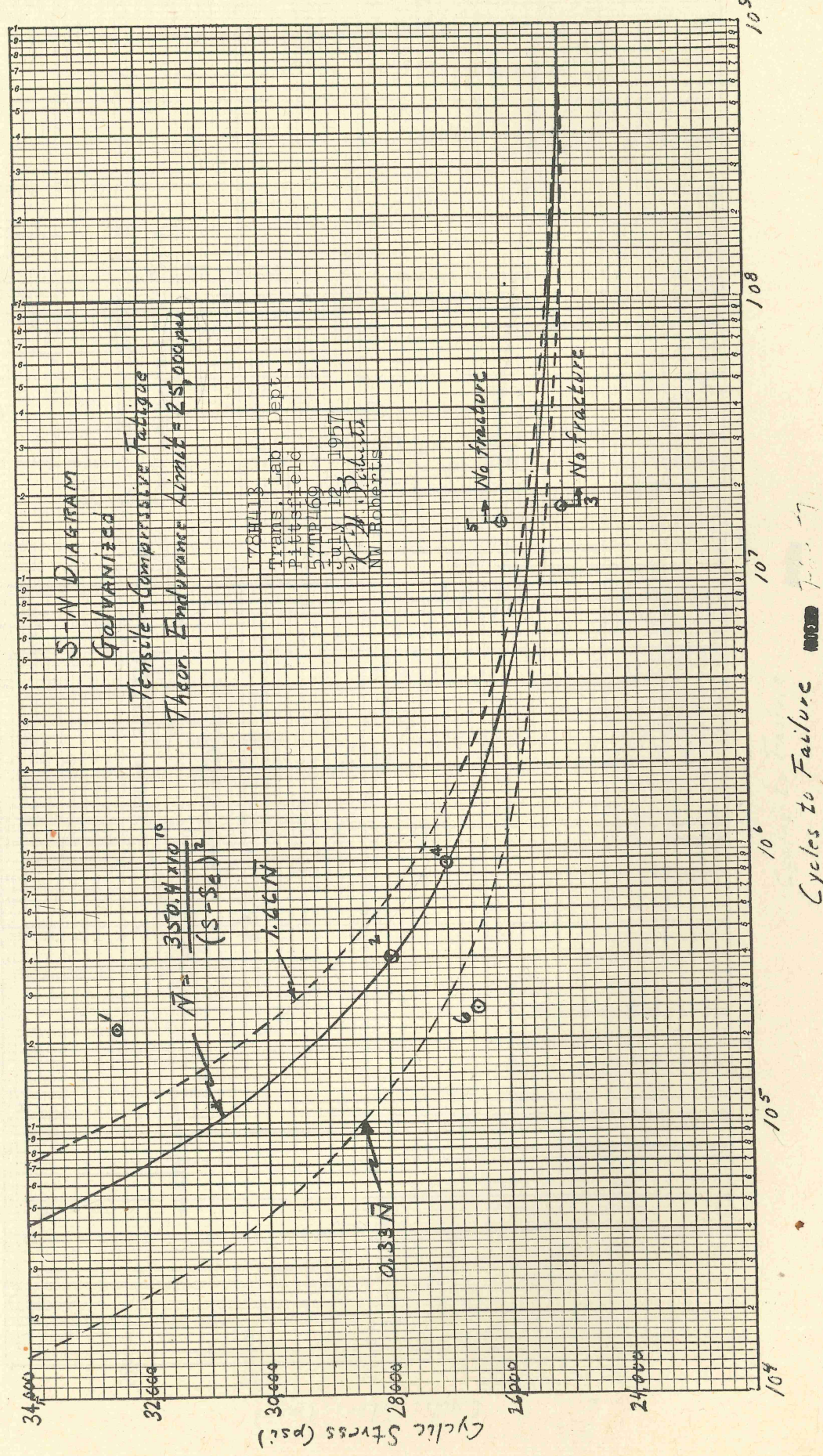
10,500



Cycles to Failure 7-24-57

178H413

7620



178H414

